Testing the Isotropy of Signal Propagation Using Distributed Precision Timing

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Abstract

The isotropy of the speed of light is a foundational assumption in modern physics, strongly supported by numerous experimental tests. However, many of these tests primarily constrain the constancy of the two-way (round-trip) speed of light and have been conducted within relatively limited spatial, velocity, and environmental regimes. This work proposes a distributed timing experiment using spacecraft and high-precision clocks to probe potential anisotropies in signal propagation across extended baselines and varying conditions. By analyzing residual timing deviations relative to standard relativistic predictions, the experiment aims to determine whether isotropy holds universally or represents an approximation valid within currently tested regimes. Any detected anisotropy could influence the interpretation of long-distance signal measurements and inform our understanding of the underlying structure of spacetime.

1 Introduction and Motivation

The isotropy of the speed of light is a central assumption in modern physics, particularly in special relativity, and is strongly supported by a wide range of experimental tests. This assumption underlies both theoretical formulations and practical systems such as the Global Positioning System (GPS) [3].

Many experimental confirmations of relativity, however, primarily constrain the constancy of the *two-way (round-trip)* speed of light. Direct empirical determination of one-way propagation properties over large distances remains fundamentally dependent on synchronization conventions, limiting the range of conditions under which directional propagation symmetry has been independently tested.

As a result, existing tests of isotropy have been conducted primarily within:

- local or near-Earth environments
- relatively limited spatial baselines compared to interstellar or intergalactic scales
- modest relative velocity regimes between experimental platforms

These constraints leave open the possibility that directional or environment-dependent propagation effects, if present, may not be detectable within currently explored regimes.

This work proposes an experimental framework designed to extend empirical testing of signal propagation into regimes involving larger spatial scales, broader environmental variation, and greater relative motion, with the goal of determining whether isotropy holds under these expanded conditions.

The experiment is designed to test whether the isotropic propagation model yields a self-consistent description of timing relationships across a distributed, multi-path measurement system. Any systematic inconsistency would indicate a deviation from isotropic signal propagation.

This is a test of consistency rather than a direct measurement of one-way propagation speed. A non-null result would indicate a breakdown of the isotropic model and could provide a physically constrained framework for defining one-way propagation and synchronization across distance.

The experiment therefore tests whether signal propagation is self-consistent under the isotropic assumption when evaluated across a distributed, multi-directional measurement system.

2 Hypothesis

Signal propagation may exhibit a physical (Type A) anisotropy relative to an underlying structure or preferred frame, with propagation characteristics depending on direction, velocity, or environment.

No assumption is made regarding the magnitude or functional form of this effect.

3 Null Hypothesis

Signal propagation is isotropic and fully consistent with predictions from special and general relativity within experimental precision.

4 Toy Model of Anisotropy

As an illustrative model, consider a direction-dependent propagation speed:

$$c(\theta) = c_0 \left(1 + \alpha \cos\theta\right)$$

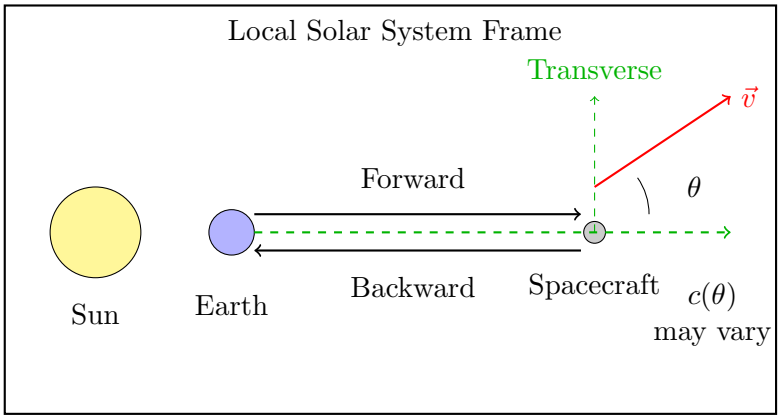
where:

- c_0 is the standard (isotropic) speed of light
- α is a dimensionless parameter characterizing the magnitude of anisotropy
- θ is the angle between the signal propagation direction and the velocity of the local frame relative to a possible preferred frame

In this model, $\alpha = 0$ corresponds to isotropic propagation. Nonzero values of α introduce directional dependence in the propagation speed.

This model is not assumed to describe physical reality, but serves as a simple framework for illustrating how directional anisotropy could manifest in measured timing data.

5 Conceptual Diagram



The vector $\vec{v}$ represents the velocity of the local frame (Earth/spacecraft system) relative to a possible preferred frame. The angle θ defines the direction of signal propagation relative to this motion.

The spacecraft follows its own inertial trajectory within the local frame; however, the anisotropy under consideration depends on the motion of the local frame relative to the underlying structure, rather than on the spacecraft's motion alone.

6 Experimental Framework

A distributed timing system is established between Earth and spacecraft equipped with ultra-precise clocks.

Continuous bidirectional communication records:

- Earth transmission times
- spacecraft reception times (local clock)
- spacecraft transmission times
- Earth reception times

7 Multi-Directional Measurement Strategy

Because the direction of any potential preferred-frame velocity $\vec{v}$ is not known a priori, measurements must be conducted across multiple propagation directions.

A set of spacecraft deployed along distinct trajectories enables sampling of signal propagation over a range of angles θ. This approach allows detection of directional dependence and, if present, reconstruction of anisotropy patterns.

8 Experimental Architecture

8.1 Local Calibration Constellation

A heliocentric constellation of spacecraft is deployed with orbital parameters similar to Earth's, maintaining approximate angular separations (e.g., $\sim 120^\circ$ spacing).

These spacecraft share a common heliocentric dynamical frame and remain in stable relative configurations over time.

8.2 Deep-Space Measurement Probes

Spacecraft are deployed along multiple non-coplanar trajectories extending away from the solar system.

Configurations may include:

- tetrahedral geometry (4 probes)
- octahedral geometry (6 probes)

These geometries enable sampling across three-dimensional space and allow reconstruction of potential anisotropy patterns.

8.3 Closed-Loop Timing and Communication

Signals are exchanged bidirectionally between Earth, the local constellation, and deep-space probes.

This distributed architecture enables:

- redundancy in measurements
- consistency checks across independent signal paths
- isolation of propagation effects from clock drift and system errors

This distributed and redundant architecture is necessary to construct multiple independent timing paths and closed loops, which are essential for distinguishing physical propagation effects from synchronization and clock-related artifacts.

9 Measurement Methodology

Residual timing differences are computed as:

$$\Delta t = t_{\text{observed}} - t_{\text{predicted}}$$

where $t_{\text{predicted}}$ is derived from the isotropic propagation model.

The objective is to identify systematic deviations from predicted timing relationships.

The sensitivity of the experiment is determined by timing precision and path length. Even small deviations from isotropy may produce measurable residuals over sufficiently large baselines, motivating the use of deep-space trajectories in combination with high-precision timing systems.

10 Synchronization and Detection Framework

10.1 Conceptual Overview

Measurements of one-way signal propagation are, in general, dependent on clock synchronization conventions. Rather than attempting to directly determine absolute one-way propagation speeds, the proposed experiment adopts the isotropic assumption as a working model to define both synchronization and predicted timing relationships across the distributed system.

Under this assumption, signal propagation occurs at a constant speed c_0 in all directions, enabling construction of a consistent synchronization protocol and a complete set of expected timing relationships between all nodes in the network.

The experiment tests whether observed timing data are consistent with these predictions by evaluating residuals:

$$\Delta t = t_{\text{observed}} - t_{\text{predicted}}$$

While individual one-way timing measurements depend on synchronization conventions, certain combinations of measurements do not. In particular, round-trip signal times and closed-loop timing relationships are invariant under synchronization choices. The proposed experiment leverages this property by constructing an over-constrained system of timing measurements across multiple independent paths.

In the isotropic case, all such timing relationships are mutually consistent and reduce to a single geometric model. In the presence of anisotropy, directional variations in propagation introduce systematic inconsistencies between different paths and loops. These inconsistencies

cannot be eliminated by any synchronization convention derived from the isotropic assumption, because they arise from physical differences in propagation rather than coordinate definitions.

Clock drift and timing offsets affect measurements in a common-mode manner and can be isolated through redundancy and cross-comparison. In contrast, anisotropy produces direction-dependent deviations that vary across paths and geometries.

Thus, the experiment detects anisotropy not by directly measuring one-way propagation speeds, but by identifying directional inconsistencies in timing relationships that remain after applying the isotropic framework.

10.2 One-Way and Round-Trip Propagation Example

Consider the model:

$$c(\theta) = c_0(1 + \alpha \cos\theta)$$

Define $\epsilon = \alpha \cos\theta$.

Forward propagation time:

$$t_f = \frac{L}{c_0(1+\epsilon)} \approx \frac{L}{c_0}(1-\epsilon)$$

Reverse propagation time:

$$t_b = \frac{L}{c_0(1-\epsilon)} \approx \frac{L}{c_0}(1+\epsilon)$$

The round-trip time is:

$$t_{\mathrm{RT}} = t_f + t_b = \frac{2L}{c_0}$$

Thus, the round-trip speed remains c_0, even if one-way propagation speeds differ.

The directional difference:

$$\Delta t = t_b - t_f \approx 2\epsilon \frac{L}{c_0}$$

demonstrates that anisotropy can exist without violating round-trip constancy, but is not directly observable through round-trip measurements alone.

10.3 Closed-Loop Detection and Reconstruction of Anisotropy

Consider a closed loop $A \to B \to C \to A$.

For each segment:

$$t_{ij} \approx \frac{L_{ij}}{c_0}(1 - \alpha \cos\theta_{ij})$$

Summing:

$$t_{\mathrm{loop}} = \sum_{ij} t_{ij}$$

$$t_{\mathrm{loop}} \approx \sum \frac{L_{ij}}{c_0} - \alpha \sum \frac{L_{ij}}{c_0} \cos\theta_{ij}$$

Define:

$$t_{\mathrm{geom}} = \sum \frac{L_{ij}}{c_0}$$

$$\Delta t = t_{\text{loop}} - t_{\text{geom}}$$

Then:

$$\Delta t = -\alpha \sum \frac{L_{ij}}{c_0} \cos\theta_{ij}$$

Using:

$$\cos\theta_{ij} = \hat{n}_{ij} \cdot \hat{v}$$

we obtain:

$$\Delta t = -\alpha \left(\sum \frac{L_{ij}}{c_0} \hat{n}_{ij} \right) \cdot \hat{v}$$

Define:

$$\vec{K} = \sum \frac{L_{ij}}{c_0} \hat{n}_{ij}$$

so that:

$$\Delta t = -\alpha (\vec{K} \cdot \hat{v})$$

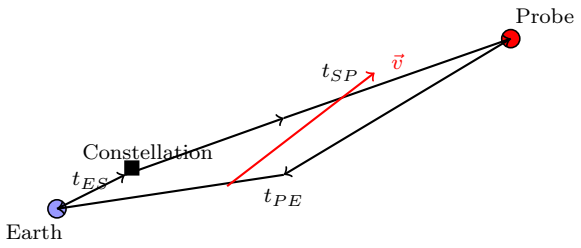
For multiple measurements:

$$\Delta t_i = \vec{K}_i \cdot \vec{V}, \quad \vec{V} = -\alpha \hat{v}$$

With sufficient independent measurements across non-coplanar directions, $\vec{V}$ (and thus $\vec{v}$) can be reconstructed.

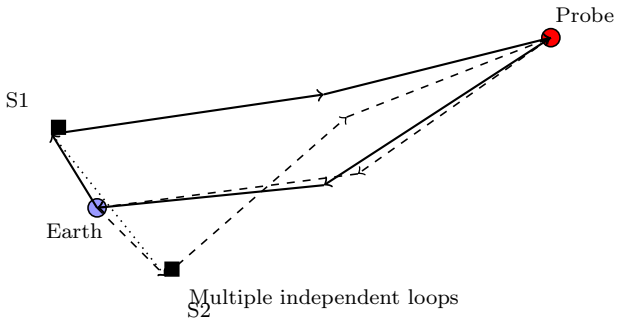
Because loop sums are invariant under synchronization conventions, this method detects physical anisotropy independently of synchronization assumptions.

10.4 Closed-Loop Mapping to the Experimental System



Closed-loop with dominant long-baseline segment

10.5 Multiple Loops and Redundancy



Multiple independent loops

These multiple independent loops provide redundant constraints, enabling detection of directional inconsistencies that cannot be attributed to synchronization or clock drift.

In these configurations, the contribution of local signal paths (e.g., Earth to constellation spacecraft) is negligible compared to long-baseline propagation to deep-space probes. As a result, any anisotropy effects are dominated by the extended propagation segments, while local measurements primarily serve calibration and consistency-check roles.

11 Implications for Signal Interpretation

If physical anisotropy exists, it may affect interpretation of signals over large distances.

- **Doppler Measurements:** Direction-dependent propagation could alter the relationship between observed frequency shifts and inferred velocities, potentially affecting astrophysical redshift interpretation.
- **Long-Distance Timing:** Propagation delays may become direction- or path-dependent over large baselines.
- **Synchronization:** High-precision synchronization across large distances may exhibit inconsistencies under isotropic assumptions.

12 Related Work and Prior Experiments

Numerous experiments have tested aspects of light propagation and relativity, including:

- Michelson–Morley-type experiments [1]
- Modern optical cavity experiments [2]
- Satellite-based timing systems such as GPS [3]
- Deep-space tracking experiments [4]
- Tests within the Standard-Model Extension (SME) framework [5]

These experiments strongly constrain deviations from isotropy within currently accessible regimes. However, they primarily probe local or near-Earth conditions, limited spatial scales, and relatively modest velocity differences between experimental platforms.

As a result, it remains possible that direction- or velocity-dependent propagation effects, if present, could remain below current detection thresholds in these regimes while becoming observable under extended baselines or higher relative velocities.

The proposed experiment complements these tests by extending sensitivity to larger spatial scales, multi-directional propagation paths, and regimes not directly probed by existing measurements.

13 Expected Outcomes

13.1 Null Result

$\Delta t \approx 0$, consistent with isotropic propagation within tested regimes.

13.2 Non-Null Result

Systematic residuals indicating directional, velocity-dependent, or environmental variation in propagation behavior.

A positive detection would consist of reproducible, direction-dependent timing residuals that cannot be reconciled with the isotropic propagation model across all paths and loops. In particular, inconsistencies between closed-loop timing relationships would indicate a breakdown of isotropic propagation assumptions.

14 Conclusion

This work proposes a direct empirical test of a foundational assumption in modern physics: the isotropy of signal propagation. By extending measurement regimes in spatial scale, environmental variation, and relative motion, the proposed experiment aims to determine whether isotropy remains consistent under broader conditions than those currently tested.

The proposed experiment complements existing tests by directly probing regimes that have not been extensively explored in combination.

A null result would further strengthen confidence in existing theoretical frameworks across an expanded domain. A non-null result, if observed, would warrant careful investigation and could suggest that current models represent highly accurate approximations within certain regimes, analogous to the relationship between Newtonian mechanics and relativity.

In either case, the outcome contributes to refining our empirical understanding of signal propagation and its role in physical theory.

References

References

[1] A. A. Michelson and E. W. Morley, "On the Relative Motion of the Earth and the Luminiferous Ether," American Journal of Science, 1887.

[2] S. Herrmann et al., Phys. Rev. D, 2009.

[3] N. Ashby, Living Reviews in Relativity, 2003.

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